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ABSTRACT

Higher-order modes are controllably excited in water-filled kagomè-, bandgap-style, and simplified hollow-core photonic crystal fibers (HC-PCF). A spatial light modulator is used to create amplitude and phase distributions that closely match those of the fiber modes, resulting in typical launch efficiencies of 10–20% into the liquid-filled core. Modes, excited across the visible wavelength range, closely resemble those observed in air-filled kagomè HC-PCF and match numerical simulations. These results provide a framework for spatially-resolved sensing in HC-PCF microreactors and fiber-based optical manipulation.

Keywords: Photonic crystal fibers, Microstructured fibers, Spatial light modulators

1. INTRODUCTION

The controlled excitation of higher-order fiber modes has become an essential part in photonics research with a range of interdisciplinary applications. For example, spatial light modulator (SLM)-based wavefront shaping techniques [1] have enabled the controlled excitation of coherent mode superpositions in multimode fibers [2], with novel applications in lensless endoscopic imaging [2]-[4] and fiber-based optical trapping [5]. In fiber communication systems, mode-division multiplexing has been used to improve data transfer rates [6]-[9].

All this previous work aims to control the light field at the end-face of glass-core fibers. In hollow waveguides, on the other hand, well-defined modal intensity distributions can be used to study light-matter interactions within the core. In particular, hollow-core photonic crystal fiber (HC-PCF) has enabled the stable and low-loss transmission of modes along microchannels [10]. The main classes of HC-PCF include bandgap-type HC-PCFs, in which a narrow transmission window is supported by the formation of photonic bandgaps in the microstructured cladding, and kagomé- and simplified HC-PCFs [11], whose broadband guidance mechanism relies on anti-resonant reflection. It has previously been shown that spatial light modulators (SLM) can be used to dynamically change between different modes in air-filled hollow-core photonic crystal fibers (HC-PCFs) [12], with applications in optical trapping [13], Raman amplification [14], telecoms [15], and quantum optics [16].

Here we extend this work to liquid-filled HC-PCFs, where guidance properties are preserved by infiltrating both the core and cladding channels [17]-[18]. Control over modal fields within these optofluidic waveguides would enable new fiber-based sensing and optical manipulation approaches.

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2. EXPERIMENTAL SETUP

We employ a method based on a spatial light modulation scheme recently presented by Flamm *et al.* [18] to controllably excite higher order modes into the liquid-filled hollow-core photonic crystal fibers (HC-PCFs). This is achieved by creating an intensity and phase distribution [20] that matches the HC-PCF mode and projecting it onto the fiber's end face. In Section A of Figure 2, light from a supercontinuum laser (NKT SuperK Compact, 450–2400 nm) is passed through a variable bandpass filter (NKT SuperK Varia, 400–840 nm), expanded and linearly polarized. A 30 cm long HC-PCF is mounted between two custom-made pressure cells (PCs), that are fitted with sapphire windows allowing for unobstructed optical access (Section C). A phase-only SLM (Meadowlark P512-480-850-DVI-C512x512) with broadband mirror coating shapes the beam and projects it in a 4-f configuration onto the fiber (Section B). Cam 2 measures the back-reflected light to help with the alignment process. With a microscope objective the transmitted mode is imaged onto Cam 3 (Section C). Cam1, in Section D, is used to verify the SLM generated intensity profiles, see examples in Figure 3.

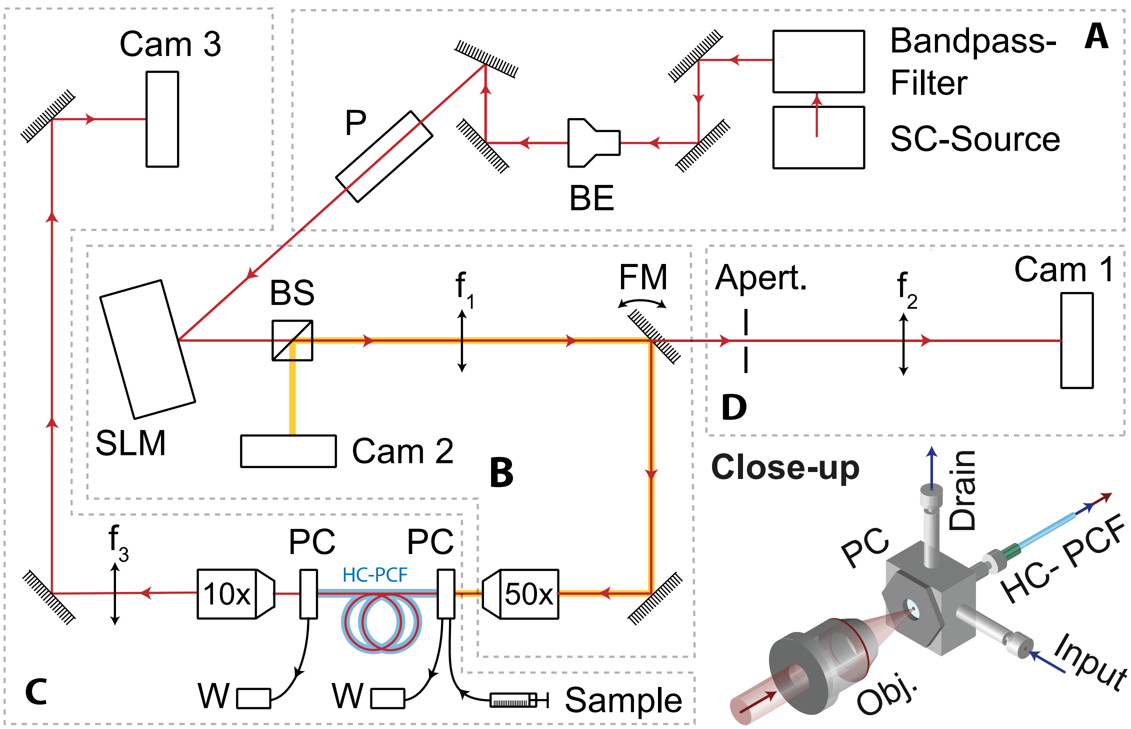

Figure 1. Setup schematic. Section A: filtering, expansion, and polarization of the input beam. Section B: modulation by phase-only SLM and projection onto the input-face of an HC-PCF. Section C: imaging of the end-face of the liquid-filled HC-PCF, enclosed by two pressure cells (PC). Section D: verification of the intensity distribution projected onto the HC-PCF. BE, beam expander; BS, beam splitter; Cam, camera; FM, flip mirror; Apert., aperture; P, polarizer; W, waste. Figure reproduced from [21].

3. MODE EXCITATION

Efficient mode excitation was achieved with Laguerre-Gaussian beams ($LG_p^{(\ell)}$). The electric field distribution in the focus of an LG beam is given by [22]:

$$E_{\mathrm{p}}^{(\ell)}(r,\phi) \sim e^{-r^2/w^2}\left(\frac{r}{w}\right)^{|\ell|} L_{\mathrm{p}}^{|\ell|}\left(\frac{2r^2}{w^2}\right) e^{i\phi\ell}, \tag{1}$$

where ℓ and p denote the azimuthal and radial order of the modes respectively, $L_{\mathrm{p}}^{(|\ell|)}$ are the generalized Laguerre polynomials, r and ϕ are polar coordinates in the focal plane and w is the beam waist. To excite a specific mode, pairs of LG beams with an appropriate relative phase were chosen. For example, the predicted LP_{31} mode (Fig. 2a) is well approximated by a superposition of $LG_0^{(3)}$ and $LG_0^{(-3)}$ beams (Fig. 2b). Mode-excitation experiments were performed in three different water-filled HC-PCFs including the bandgap HC-PCF, the kagomé HC-PCF, and the simplified HC-PCF. Figure 3 shows the measured intensity distribution of an LP_{11} mode excitation in each one of these fibers. Additional excited modes and a more detailed analysis can be found in [21].

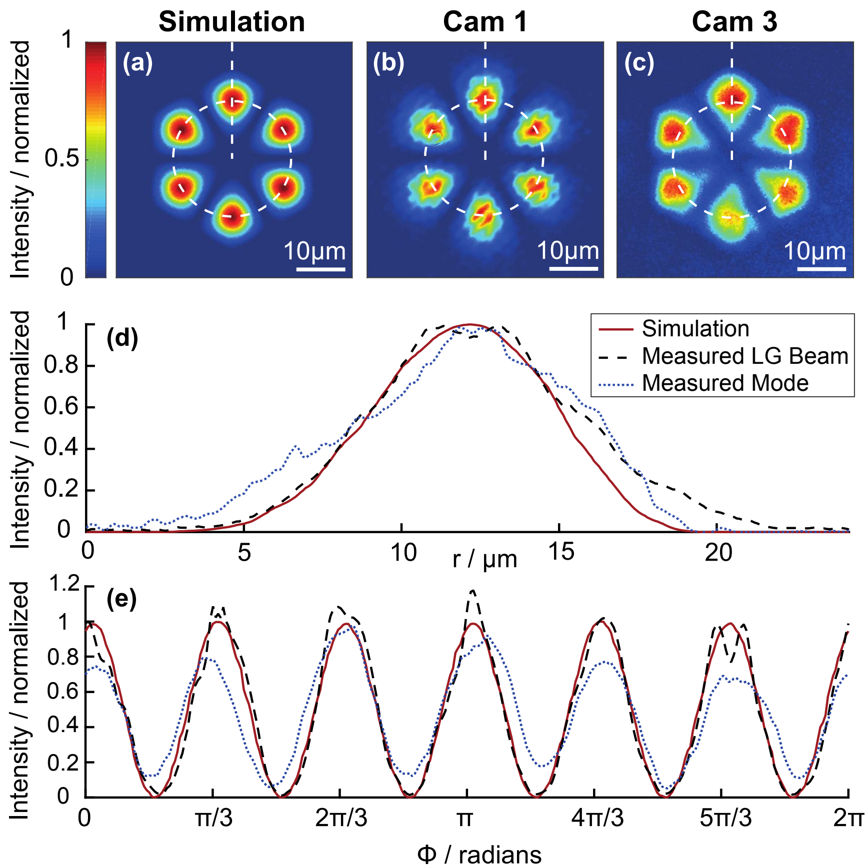

Figure 2. Mode excitation example: (a) Simulated intensity profile of a LP_{31} core mode in the kagomé PCF. (b) Measured intensity of an $LG^{(3)} + LG^{(-3)}$ beam profile. (c) Measured intensity profile of the excited LP_{31} fiber mode. Radial- (d) and azimuthal (e) sections along the dashed curves in (a–c). Figure reproduced from [21].

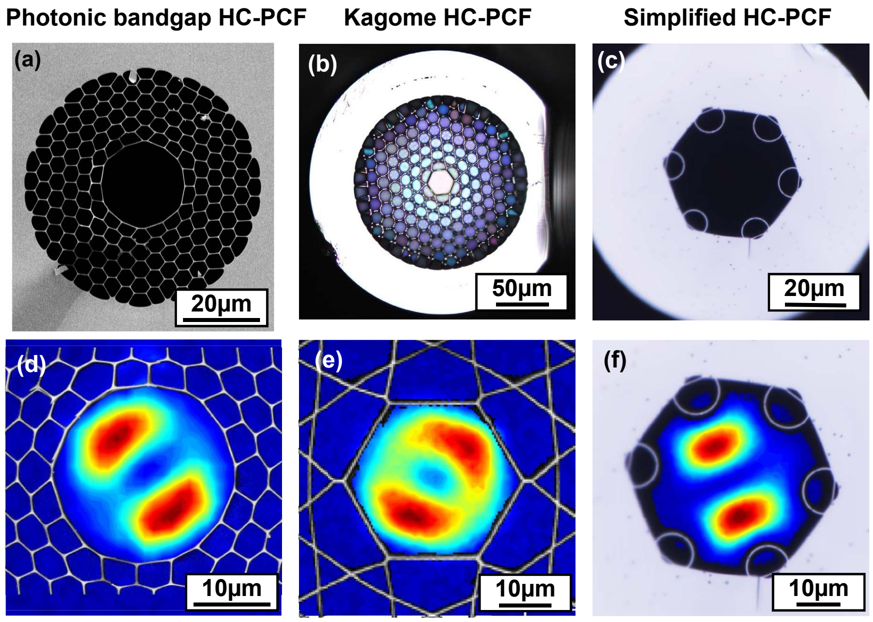

Figure 3. Mode excitation in fibre: Measured intensity profile of a LP_{11} core mode (d)-(f) in the photonic bandgap HC-PCF, kagomé HC-PCF and simplified HC-PCF (a)-(c).

4. CONCLUSION AND OUTLOOK

We demonstrate a spatial light modulation setup that can be used to efficiently excite higher-order modes in liquid-filled HC-PCFs. The setup was tested on three different types of water-filled HC-PCFs (bandgap, kagomé, and simplified). While the observed modes were relatively pure and launch efficiencies high (10–20%), further improvements could be made by correcting for aberrations in the optical system and using a more robust hologram optimization routine.

The results provide a framework for new spatially-resolved sensing and optical manipulation experiments in liquid-filled hollow-core PCF. Measurements using different spatial modes would enable the probing of chemicals at varying distances from the core wall and thus provide a direct measurement of surface effects and microscale diffusive transport, both of which are rate-limiting factors in HC-PCF microreactors [23] and flow-chemistry in general. In optical manipulation studies, superpositions of higher-order modes can be used to create reconfigurable 3-D intensity patterns within the hollow core [13] that could be used to trap, transport, and separate micro- and nanoparticles along the fluid channel.

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